Extrude Hone Corporation

Flow-Control Machining

In the mid-1990s, internal automotive engine parts often had manufacturing imperfections (such as roughness, size, and balance) that decreased performance. Finishing processes to correct the imperfections were time consuming and expensive. Extrude Hone Corporation formed a joint-venture partnership with Ford Motor Company, General Motors (GM), the University of Nebraska, and the University of Pittsburgh to develop two new, automated, and cost-effective finishing processes for cast-metal parts that carry fluids in interior passageways. Called abrasive flow-control machining (AFCM) and nontraditional combustion chamber sizing (NCCS), the processes could increase the precision of airflow and fuel blends, leading to a six-percent increase in fuel economy, as well as improved performance and reduced emissions. The technologies had high technical risks: researchers would need to develop new computer-generated models, new methods of manufacturing control, and new forms of abrasion used to smooth the parts. They would need to devise methods to monitor the flow rate of the abrasive medium in real time. “Machining to function,” or taking measurements in real time to reach specifications, represented a radical departure from industry practice. For these reasons, the joint venture was unable to obtain conventional financing and applied to the Advanced Technology Program (ATP).

ATP approved funding for a four-year project as part of a 1995 focused program, “Motor Vehicle Manufacturing Technology.” The joint venture achieved most of its technical goals. They developed preliminary commercial applications, such as a limited production run of the Ford Contour SVT model, while the project was ongoing, which gained six horsepower. Extrude Hone and Ford received attention in numerous publications, and Extrude Hone received seven patents for innovations associated with the ATP-funded project. However, Ford and GM later decided not to use the process for the automotive mass market due to the additional cost associated with flow-control machining. Extrude Hone continues to use the technology in custom applications for performance cars. They have further advanced the technology for ultra-fine applications, such as small-hole diesel spray nozzles to increase performance and reduce emissions and coin die manufacturing. In 2005, Extrude Hone was acquired by Kennemetal, Inc. and won a three- to five-year contract with GM to use abrasive-flow machining to machine the exhaust ports and head for a supercharged Cadillac STSV, beginning with the 2007 model year. GM expects to sell 7,000 units per year.

COMPOSITE PERFORMANCE SCORE

(based on a four star rating)

* * * *

Research and data for Status Report 95-02-0058 were collected during January – February 2006.

Engine Performance Is Limited by Imperfections in Airflow

Intake manifolds and ports are engine parts that are too complex to machine from a solid block. Instead, these parts are made of cast aluminum. The size and smoothness of the manifolds and ports depend on the quality of the design and the casting process. Imperfections and sharp edges formed in the casting process cause deviations from optimal airflow and fuel mixtures. If flow is too low, the engine operates inefficiently. If flow is too high, the combustion chamber may “ping” due to over-compression. Repeated over-compression damages an engine, so most automobile designers build in a safety margin, which sacrifices efficiency. If the air and fuel distribution could be more precise, engines could operate with higher horsepower, higher efficiency, and lower emissions.

Creating ultra-smooth surfaces is known as honing. Reduced friction decreases heat and wasted energy in engines. In the mid-1990s, manufacturers of specialty, high-performance engines used a manual, iterative process called abrasive flow machining (AFM), which injected a viscoelastic media (similar to “silly putty”) with grit added to smooth, size, and balance the fluid flow chambers. Extrude Hone Corporation, a small business focused on machining precision, used the viscoelastic media. Extrude Hone was so named because the abrasive media are forced (or extruded) through a manifold’s passages like dispensing frozen yogurt from a machine (see Figure 1), then used to "hone" or polish sensitive machinery. The media abrade or polish the areas with the greatest restriction in the flow path. Each manifold is then measured for airflow, flow-machined (polished), measured again, then flow-machined again until it meets specifications. This manual process is labor intensive and expensive.

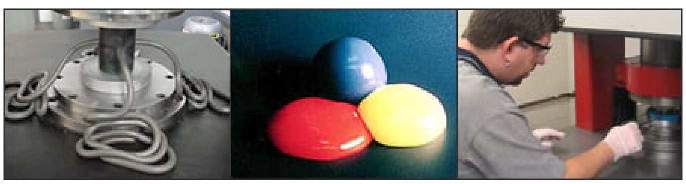

Figure 1. Extrude Hone’s abrasive media (similar to “silly putty”) has grit added to smooth, size, and balance the fluid flow chambers. Extrude Hone patented the manual AFM process in the 1960s as a method to deburr and polish difficult-to-reach interior surfaces.

Joint Venture Proposes to Automate AFM

Extrude Hone Corporation had already invested $3 million over six years to improve mechanical performance and delivery in small, incremental steps. Their previous projects had been constrained to small, incremental improvements, due to customer requirements for a rapid return on investment. Therefore, Extrude Hone turned to potential users Ford Motor Company and General Motors (GM), as well as researchers in neural-network models for process control equipment at the University of Nebraska and the University of Pittsburgh. (Subcontractors included Roush Industries, an engine designer; CMI Castings, a manufacturer of aluminum intake manifolds and cylinder heads; and ALCOA, a supply chain advisor.)

If the air and fuel distribution could be more precise, engines could operate with higher horsepower, higher efficiency, and lower emissions.

Extrude Hone’s joint venture would develop an innovative, new automated platform technology called flow-control machining (FCM). Automated FCM represented a dramatic change for auto manufacturing; FCM development carried with it a level of high technical risk, including process integration. FCM would consist of two new automated and cost-effective finishing processes for the cast-metal parts that carry fluids in interior passageways: abrasive flow-control machining (AFCM) and nontraditional combustion chamber sizing (NCCS). Specifications would be measured in real time during machining, called “machining to function.” If successful, the new processes could increase the precision of the airflow and fuel blends, leading to a six-percent increase in fuel economy, as well as improved performance.

Radical Approach Departs from Industry Practice

The approach of “machining to function” was a radical departure from automotive industry practice, which had been historically conservative. This approach would eliminate the iterative process of machining, measuring, then machining again. Taking FCM technology to a higher level had the following technical risks:

- In order to enable, predict, and control machining processes, the Extrude Hone team needed to understand the relationship between the flow of abrasive media (silly putty) and the flow of fuel and air in the finished part. They also needed to optimize the media composition and address the nature of abrasive medium, which does not behave in Newtonian ways (that is, like silly putty, it will flow if force is applied slowly, but it will resist flow if force is applied rapidly).

- The parts to be machined were highly complex; therefore, it was unlikely that an analytic solution to the FCM could be reached. The project required a strong experimental and statistical component. Researchers would collect extensive data on before- and after-air flows of specific component test pieces, along with continuous process flow data to populate a large information base. They would also search for correlations between air flow and AFM media flow. Based on these data, they would develop algorithms. Iterative algorithm development on different components would reduce the time and cost of start-up for new applications.

- Monitoring the flow rate of the machining medium in real time at high resolution required new process control methods, computer network systems, and abrasion techniques.

If successful, FCM could lead to economic and environmental benefits for aircraft, diesel, and automotive engine applications by increasing the functional precision and efficiency of cast-metal parts that carry fluids in interior passages. Extrude Hone asserted that FCM could result in a cumulative six-percent reduction in fuel consumption, as follows:

- Two percent from increasing airflow capacity in intake manifolds by 15 percent
- Two percent from increasing airflow capacity of intake ports in cylinder heads by eight percent (without increasing valve diameter)
- Two percent from improved precision of combustion chambers, leading to a 0.225 increase in the compression ratio (compression ratio is the ratio of the volume of the air–gas mixture when the piston is at the bottom of its stroke to the volume of the mixture when the piston is at the top of its stroke)

The average fuel efficiency standard for passenger cars since 1990 was 27.5 mpg, so a 2-percent increase in fuel efficiency would raise the average to 28.05 mpg. Based on an average 15,000 miles per year, this would represent a fuel savings of 10.2 gallons a year.[1] In addition, increased and balanced airflow could increase horsepower and reduce emissions. More horsepower could allow automakers to add options and safety equipment without compromising fuel economy. Decreased emissions would protect the environment. Automated FCM would make the process affordable for mass-market passenger-vehicle engines.

Because of the high technical risk, the Extrude Hone joint venture was unable to obtain commercial funding. The companies applied for and received cost-shared funding in 1995 from ATP for a four-year project under the “Motor Vehicle Manufacturing Technology” focused program; their project was later extended by six months at no additional cost.

AFCM Follows Four-Task Strategy

Rather than achieving small, incremental steps, the Extrude Hone joint venture intended to make a leap forward in FCM technology. The ATP-funded FCM project had two parts: AFCM and NCCS. The AFCM process would consist of cylinders to extrude the abrasive media through passages in the part. Abrasive action would occur wherever the media entered and passed through the most restrictive passages (see Figure 2).

Figure 2. Cutaway view of the interior of a Ford intake manifold before and after manual AFM processing. Note the polished interior finish on the bottom, which allows fuel and air to flow quickly.

[1]Corporate Average Fuel Economy (CAFE), National Highway Transportation Safety Board, http://www.nhtsa.dot.gov/cars/rules/cafe/overview.htm; Retail Motor Gasoline and On-Highway Diesel Fuel Prices, 1949-2004 (Dollars per Gallon), Energy Information Administration, http://www.eia.doe.gov/emeu/aer/txt/ptb0524.html.

The AFCM part of the ATP-funded project involved four tasks:

- **Task 1:** Develop the correlation between passage air flow resistance and flow resistance to abrasive media during AFM processing. Establish the initial feasibility of nontraditional combustion chamber cavity-sizing processes.

- **Results:** Extrude Hone outfitted existing AFM equipment with new flow-control and monitoring components. A neural-network model took into account rheology (the deformation and flow of matter), continuum mechanics, and fluid dynamics. The model received data from the monitoring equipment, the pre-machining airflow, and the real-time viscoelastic flow ratios. Researchers correlated media flow with after-machining measurements of airflow. They optimized media formulations, operating temperature, cool-down cycles, and media-refresh rates. They reduced the amount of media used to achieve required cubic-feet-per-minute levels, from 45,000 to 15,000 cubic inches.

- **Task 2:** Design and build pre-prototype systems to develop real-time machining algorithms.

- **Results:** The group built a laboratory prototype AFCM machine, developed algorithms, and collected data to correlate and optimize machining conditions with outcomes.

- **Task 3:** Verify process robustness by processing components using the machining algorithms.

- **Results:** The group ran the prototype machine on 5,000 intake manifolds, testing the algorithms by calibrating the machine on different cast-metal pieces. All polishing was performed parallel to the air/fuel flow. The result was a surface finish "grain" achieved in the same direction. This unidirectional flow allowed the media to exit freely from the part for fast `processing, easy cleaning, and simple, quick exchange tooling. They developed acoustic sensors to measure smoothness during processing.

- **Task 4:** Install and integrate the machining cells (machining assemblies) into the supply process to demonstrate and mature the technology.

- **Results:** The group installed a production line with a video link to the technical support group. They integrated the acoustic equipment into a laboratory prototype of the online manufacturing cell to measure performance in real time.

Based on the positive results of the AFCM portion of the project, the Extrude Hone group expected to be able to apply automated FCM to a wide class of intake manifolds and ports.

NCCS Involves Four-Task Work Process

Most internal combustion engines have combustion chambers (pistons) where fuel is mixed with air and is ignited. Chamber volumes vary due to imperfections created during casting, leading to uneven combustion levels. Nontraditional combustion chamber sizing (NCCS) aimed to increase the functional precision of combustion chambers. As of 1995, the state-of-the-art was to machine the surface of the cylinder head so that the chambers had volumes as similar as possible. For high-performance engines, chamber sizing meant manually grinding the interior of all but the largest chamber until they matched. Precision was problematic, because irregular shapes made accurate measurements difficult.

Flow-control machining could lead to economic and environmental benefits for aircraft, diesel, and automotive engine applications.

During the NCCS portion of the project, the researchers would develop an automated and cost-effective process to accurately measure and size combustion chambers. Decreasing variation in volume would increase the compression ratio by 0.225 and increase fuel efficiency by two percent. Extrude Hone initially planned to follow a four-task work strategy; however, the joint venture was not able to complete Tasks 2, 3, and 4.

- **Task 1:** Evaluate three measuring/sizing processes for their effectiveness: orbital abrasion (using a fine grit, similar to AFM, in the combustion chamber), electrochemical machining (using a brine and electrical charge to machine the surface), and electrochemical orbital abrading (a hybrid of the first two processes). The goal was to reach a machining accuracy of $\pm$ 0.2 cc. Improved machining and subsequent increased precision of the combustion chambers would contribute to an increase in fuel efficiency.

- **Results:** The results were mixed. Measuring the combustion chamber volumes was difficult. The hybrid process failed because the metals made contact and shorted the system. Extrude Hone was able to machine four combustion chambers simultaneously using the orbital abrasion process. After grinding, they improved the surface using orbital polishing. The team also completed a cathode for electrochemical machining and produced a chamber volume within the $\pm$ 0.2 cc specifications on cast aluminum heads. Machined parts showed a roughness reduction of 2.4 to 4.6 micrometers (μm).

These developments achieved during Task 1 took longer than expected, so the remaining tasks were not completed. Extrude Hone did gain an understanding of how to work in complex shapes and reduce surface roughness, and they did continue development on the following tasks after the ATP-funded project ended:

- **Task 2:** Build a laboratory prototype based on the best of the three options

- **Task 3:** Verify the process by machining 2,500 cylinder heads

- **Task 4:** Install the prototype machine in a joint-venture partner's facility for in-line testing

Early Automotive Application Contributes to Awards

While the ATP-funded project was ongoing, Ford successfully applied Extrude Hone's FCM to the cylinder heads and intake manifolds on the 1998 Ford Contour SVT. "Smoothing the surfaces and allowing for better airflow…. the gain [was] perhaps six horsepower." (*Car and Driver*, March 1997). The Contour SVT model won technical awards in 1997 and 1999 as one of the "Ten Best Engines" from *Ward's Auto World* for the 1998 and 2000 model years.

The first Ford Contour SVT using Extrude Hone's processing competed in the 1998 Michelin One Lap of America Motorsports event,[2] a race that covered 6,373 miles. The Contour was one of only three stock cars competing among 78 entries. Its fuel mileage averaged 24.5 mpg with low emissions. The car finished 4th in its class (out of 9 mid-priced sedans) and 53rd overall. The same model competed again in the 1999 event, finishing 46th out of 102 cars. In this race, 35 percent of the cars were using Extrude Hone's AFM process to smooth intake manifolds and ports, with more expected the following year. This success contributed to an expansion in Extrude Hone's niche custom automotive machining business. The ultimate goal was to apply this process to mass-manufactured automobiles.

Technical Outcomes Look Promising

As of 1999, at the end of the ATP-funded project, it appeared that Extrude Hone would meet its technical goal of increasing fuel efficiency by six percent. AFCM appeared capable of delivering a four-percent efficiency improvement. NCCS was in a more nascent stage, on track to generate an additional two-percent efficiency. However, GM decided not to pursue the technology, so Extrude Hone continued development internally. The company was awarded seven patents for its technology advances and received considerable press attention.

Although business growth was hard to quantify, the ATP-funded project enabled the company to advance its technology and process on a much larger scale, according to Bill Walch, Research Engineer with Extrude Hone. Machining to function did not turn out as anticipated, because acoustic sensors failed to recognize smoothing on the inside during operation. As a result, the company discontinued the sensors. The project's key advances were in relating media flow with air/fuel flow, optimizing the media, measuring performance outcomes, and developing algorithms to predict future performance.

Small Holes Provide Big Benefits

Based on the technology for intake manifolds advanced in the ATP-funded project, Extrude Hone introduced a new process, MicroFlow AFM, in 2000. Although

[2] http://onelapofamerica.com/history/index.shtml?y=1998. Also, Extrude Hone quarterly report dated June 30, 1998.

MicroFlow is similar to standard AFM, the main difference is that MicroFlow uses a much lower viscosity media and smaller abrasive particle size. This allows the media to flow through very small or micro-sized holes that range from 115 μm (0.004 inches) up to 750 μm (.030 inches) in diameter.

MicroFlow AFM is ideally suited to the diesel and automotive industry in the manufacture of fuel systems, particularly fuel spray-injector nozzles (see Figure 3). The process allows individual and sets of spray nozzles to be fine-tuned to a very specific, close tolerance size and flow rate. Spray nozzle holes are much smoother (with a higher quality surface finish) than standard processed holes. They have a defined exit radius that contributes to flow capacity and fuel spray distribution. Essentially, the process produces a spray nozzle with improved fuel atomization for increased engine performance and power and reduced emissions.

Figure 3. MicroFlow AFM allows diesel manufacturers to produce internal structures, controlled radii, polished surfaces, and uniform micro-sized holes previously unattainable.

Advanced high-pressure injection system components for diesel engines face high cycle fatigue challenges similar to aircraft turbine engine components. Repeated pulses of very high pressures can cause fatigue failures at high-stress areas. Smoothing removes small surface cracks and gives a uniform radius to sharp edges. Extrude Hone's MicroFlow AFM process extends component service life.

Extrude Hone Expands Commercial Applications

Extrude Hone made another technical advance following the ATP-funded project, called AutoFlow, which is a process to regulate the speed at which the media passes through the component to generate more consistent, predictable results. This technology builds on the ATP-funded AFCM process, which optimized media formulations, temperatures, algorithms, and media refresh rates. Rather than maintaining steady input pressure, Extrude Hone controls the media flow rate, which leads to more consistent machining rates. Unlike MicroFlow, AutoFlow adjusts extrusion pressure or back pressure to keep a consistent media flow rate, making adjustments as the media softens with use. AutoFlow allows more stable energy to build up in the abrasive media, keeping media properties more consistent. Extrude Hone uses AutoFlow in aerospace, dies, molds, and medical applications (such as machining implantable devices, pharmaceutical machines, or a slot on a staple slide for surgical instruments used to close incisions).

Extrude Hone introduced Orbital AFM polishing in 2000. Building on lessons learned from the ATP-funded NCCS, Orbital AFM uses rapid, precise polishing and finishing on the edges and surfaces for complex shapes and cavities, such as bottle molds, coining dies, and aluminum wheels, with even greater precision, uniformity, and accuracy than Extrude Hone's standard AFM process.

In a matter of minutes, the Orbital AFM process produces a surface finish that is 20 to 30 times smoother the original. Average surface roughness can be reduced to 0.01 μm or lower, and the surface finish often resembles a mirror. This process produces surface finishes previously unattainable by conventional polishing methods, in one-quarter of the time and cost (see Figure 4).

Figure 4. Orbital AFM polishes the edges and surfaces of complex shapes and cavities such as bottle molds, coining dies, and aluminum wheels with high precision, uniformity, and accuracy.

Orbital AFM polishing applies to a broad range of materials, including tool steel, stainless steel, mild carbon steel, aluminum, carbide, and many others. It improves the surface quality of components manufactured by conventional machining, milling, drilling, casting, forging, or molding. The U.S. Mint in San Francisco uses Extrude Hone's Orbital AFM system to obtain an ultra-fine finish on its proof sets.

The Orbital AFM process was applied to the space shuttle Atlantis' engines before its launch in 2002. The process is used by the aerospace industry to improve the strength of blades, disks, hubs, and gear shafts and is used in semiconductor fabrication and medical applications, as well.

The Orbital AFM process produces surface finishes previously unattainable by conventional polishing methods, in one-quarter of the time and cost.

In 2005, Extrude Hone was awarded a three- to five-year contract with GM for a supercharged Cadillac STSV, beginning with the 2007 model year. GM expects to sell 7,000 units per year. Extrude Hone is machining the exhaust ports and head using Orbital AFM at its facility. This arrangement was more cost effective than setting up an AFM processing center at the GM plant.

Technical and Business Success Leads to Acquisitions

Extrude Hone's business has grown as a result of its technical success. The company acquired the specialized deburring and finishing business of Robert Bosch USA in September 2000; an AFM competitor, Dynetics, in September 2001; and a thermal energy process product line from Bosch Germany in November 2002. By 2003, the company had grown to 20 locations globally and more than 400 employees and had won several business awards. Extrude Hone had consistently reinvested 10 to 15 percent of its annual revenues into research and development. In 2005, Extrude Hone spun off a separate experimental company, ExOne, which continues to conduct experimental research and development for new products and processes. These include projects to machine small orifices and three-dimensional prototyping (initiated during a second ATP-funded project funded in 1997, "Development of the 3-D Printing Process for Direct Fabrication of Automotive Tooling for Lost Foam Castings," 97-02-0055). In 2005 Kennemetal Inc., a tool and tooling systems service company, acquired Extrude Hone's machine smoothing and polishing processes.

Conclusion

Extrude Hone Corporation used this 1995 ATP-funded focused project in "Motor Vehicle Manufacturing Technology" to develop a platform technology called flow-control machining. Joint venture partners included Ford Motor Company and General Motors (GM), as well as researchers at the University of Nebraska and the University of Pittsburgh. The joint venture met most its technical goals in developing two new automated processes: abrasive flow-control machining (AFCM) and nontraditional combustion chamber sizing (NCCS). These processes were intended to facilitate "machining to function"; that is, precise, real-time measuring during the machining process in order to achieve optimal specifications.

Although the sensors for automatic measurement of conditions did not work as expected, Extrude Hone optimized media and algorithms and learned many lessons from the project. AFCM increased fuel efficiency four percent by improving the precision of the air and fuel mixtures flowing through the intake manifold and valves to the combustion chamber. (Extrude Hone developed algorithms to correlate passage air flow resistance and flow resistance to abrasive media during abrasive flow machining [AFM] processing.) NCCS improved the accuracy of machining combustion chambers, increasing fuel efficiency another two percent, but this process was never commercialized, because development took longer than expected. Extrude Hone received patents and media attention for its technology advances.

Extrude Hone continued developing AFM after the ATP-funded project ended. The company performs custom work for high-performance cars and developed three new processes that rely on advances made during this project: AutoFlow, MicroFlow AFM, and Orbital AFM. AutoFlow is used in aerospace, dies, molds, and medical applications. MicroFlow is used for small holes, such as in diesel fuel spray injector nozzles. Orbital AFM is used for ultra-fine finishes on molds and dies, such as those used to make coins. While Ford and GM determined that AFM was still too costly for the automotive mass market, Extrude Hone is beginning to enter that market. In 2005, the company received a three- to five-year contract with GM to machine the exhaust ports and heads for a supercharged Cadillac STSV, beginning with the 2007 model year.

PROJECT HIGHLIGHTS
Extrude Hone Corporation

Project Title: Flow-Control Machining

Project: To develop a flow-control finishing technique in which an abrasive liquid machines the hollow flow passages and combustion cavities in automotive engines for higher efficiency engines that consume less fuel while emitting fewer pollutants.

Duration: 9/15/1995 - 2/15/2000
ATP Number: 95-02-0058

Funding (in thousands):

ATP Final Cost	$3,907	49.3%
Participant Final Cost	4,024	50.7%
Total	$7,931	

Accomplishments: Extrude Hone accomplished most of its abrasive flow machining (AFM) technical goals. Although automated, real-time machining did not fully succeed, Extrude Hone made advances in relating media flow with air/fluid flow, optimizing the media, measuring performance outcomes, and developing algorithms to predict future performance. Technical outcomes were as follows:

- Extrude Hone related passage air-flow resistance and flow resistance to abrasive media during AFM processing. They optimized media formulations, operating temperature, cool-down cycles, and media-refresh rates. They reduced the amount of media used from 45,000 to 15,000 cubic inches.

- The company designed and built prototype systems, developed real-time machining algorithms, and collected data to correlate and optimize machining conditions with outcomes.

- The company verified process robustness by processing 5,000 intake manifolds using the new machining algorithms. They developed acoustic sensors to measure smoothness during processing, but the correlation between sound and smoothness was not as clear as anticipated. This part of the process was not successful.

- The company installed and integrated the machining cells into the supply process to demonstrate and mature the technology.

- The first stock Ford Contour SVT using Extrude Hone's processing competed in the 1998 Michelin One Lap of America Motorsports event, a 6,373-mile race. Only three stock cars competed among 78 entries. The Contour's fuel mileage averaged 24.5 mpg with low emissions. The car finished 4th in its class (of 9 mid-priced sedans) and 53rd overall out of 78 entries. In 1999, the Contour competed again, finishing 46th out of 102 cars. In this race, 35 percent of the cars used Extrude Hone's AFM process to smooth intake manifolds and ports.

- After the ATP-funded project concluded, Extrude Hone released a new process, MicroFlow AFM, in 2000. Similar to standard AFM, MicroFlow uses a lower viscosity media and smaller abrasive particles. This allows the media to flow through very small or micro-sized holes ranging from 115 micrometers (μm) (0.004 inches) up to 750 μm (.030 inches) in diameter. This technology is suitable for diesel applications.

- Extrude Hone released another process, AutoFlow, that regulates the speed the media passes through a component to generate more consistent, predictable results. Focusing on media flow rate rather than input pressure leads to more consistent machining rates.

- Extrude Hone introduced Orbital AFM Polishing in 2000. Orbital AFM provides rapid, precise polishing and finishing on the edges and surfaces of complex shapes and cavities, such as bottle molds, coining dies, and aluminum wheels, with ultra-fine precision, uniformity, and accuracy. Orbital AFM produces a surface finish that is 20 to 30 times smoother than the original. Average surface roughness can be reduced to 0.01 μm or less. This process produces superior surface finishes in one-quarter the time and cost.

Extrude Hone received two technical awards and three business awards for innovation and growth:

- "Ten Best Engines" awarded to the Ford SVT 2.5L High Output V-6 (195 horsepower), by *Ward's Auto World*, February 1997. The engine provides 25 additional horsepower over the standard production engine it is based on by applying the Extrude Hone polishing process to its upper intake manifold plenum and runners and secondary intake ports.

- "Ten Best Engines" awarded to the Ford SVT 2.5L High Output V-6 (200 horsepower), by *Ward's Auto World*, January 1999. The Extrude Hone polishing process was added to the primary intake ports as well.

PROJECT HIGHLIGHTS
Extrude Hone Corporation

- "Entrepreneur of the Year" awarded to Lawrence Rhoades, CEO of Extrude Hone, by the *Pittsburgh Business Times*, June 2003. Extrude Hone supplies half of the 100 largest manufacturers in the world and grew at an average annual rate of nearly 20 percent over 20 years. Steady growth has continued despite a 63-percent drop-off in U.S. consumption of machine tools from 1997 through 2002. During that period, Extrude Hone more than doubled sales from $24 million to more than $50 million.

- "Entrepreneur of the Year" in the master category awarded to Lawrence Rhoades by Ernst & Young, 2003. Mr. Rhoades grew the small company he bought in 1969 into Extrude Hone, which had 20 locations globally and more than 400 employees in 2003. Extrude Hone invests 10 to 15 percent of its annual revenues into research and development. In addition to technological innovation, Mr. Rhoades has developed a philosophy that a business is a social organization, and a creative workplace gives people a chance to stretch and test themselves.

- "Manufacturer of the Year" finalist, in the medium-sized category, awarded to Extrude Hone by the *Pittsburgh Business Times*, December 2003. The client roster for the company includes such high-profile names as Honeywell, Ford, Alcoa, General Electric, and Caterpillar.

Extrude Hone was awarded seven patents derived directly and indirectly from the ATP-funded machining technology advancements:

- "Method and apparatus for controlling abrasive flow machining"
  (No. 6,319,094: filed December 29, 1999, granted November 20, 2001)

- "Method and apparatus for abrading the region of intersection between a branch outlet and a passageway in a body"
  (No. 6,503,126: filed September 12, 2000, granted January 7, 2003)

- "Abrasive polishing apparatus"
  (No. 6,544,110: filed August 14, 2001, granted April 8, 2003)

- "Abrasive polishing composition"
  (No. 6,918,937: filed August 14, 2001, granted July 19, 2005)

- "High precision abrasive flow machining apparatus and method"
  (No. 6,500,050: filed August 16, 2001, granted December 31, 2002)

- "Abrasive flow machining apparatus and method"
  (No. 6,905,395: filed September 21, 2001, granted June 14, 2005)

- "Method and apparatus for measuring flow rate through and polishing a workpiece orifice"
  (No. 6,953,387: filed November 12, 2004, granted October 11, 2005)

Commercialization Status: As a result of Extrude Hone's technical and business growth, the commercial side of the company was acquired by Kennemetal in 2005. The research and development arm was spun off into a separate company, ExOne. Extrude Hone has developed several commercial processes to benefit manufacturers:

- MicroFlow AFM, released in 2000, is suitable for small-hole applications, such as fuel systems, particularly fuel spray-injector nozzles. Spray nozzles can be fine-tuned to a very close tolerance size and flow rate. Spray nozzle holes are much smoother (with a higher quality surface finish) than standard processed holes.

- AutoFlow regulates the speed the media passes through a component to generate more consistent, predictable results. Extrude Hone uses AutoFlow in aerospace, dies, molds, and medical applications (such as machining implantable devices, pharmaceuticals, or a slot on a staple slide for surgical instruments used to close incisions).

- Orbital AFM polishing provides rapid, precise polishing and finishing on the edges and surfaces of complex shapes, such as bottle molds, coining dies, and aluminum wheels, with ultra-fine precision, uniformity, and accuracy. For example, Orbital AFM enables the U.S. Mint in San Francisco to obtain an ultra-fine finish on its proof sets. In 2005, Extrude Hone was awarded a three- to five-year contract to machine exhaust ports and heads using Orbital AFM for General Motor's (GM) supercharged Cadillac STSV, beginning with the 2007 model year. GM expects to sell 7,000 units per year. Semiconductor manufacturers and medical applications also use Orbital AFM.

- Orbital AFM polishing was applied to the engines of the space shuttle Atlantis before its launch in 2002. The aerospace industry uses the process to improve the strength of blades, disks, hubs, and gear shafts.

PROJECT HIGHLIGHTS
Extrude Hone Corporation

Outlook: The outlook for Extrude Hone's AFM is strong. The company has derived three new processes, MicroFlow AFM, AutoFlow AFM, and Orbital AFM, building on the advances made during the ATP-funded project. Acquired by Kennemetal in 2005, the company continues to provide superior machining services and tools for various applications: diesel engines, ultra-fine dies (such as for coins), aerospace parts, and high-performance cars.

Composite Performance Score: * * * *

Number of Employees: 120 employees at project start, 400 as of June 2003, 110 as of February 2006 (Extrude Hone, a Kennemetal company)

Focused Program: Motor Vehicle Manufacturing Technology, 1995

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Subcontractors:

- Roush Industries
  Livonia, MI
- CMI Castings
  Southfield, MI
- ALCOA
  Pittsburgh, PA

Publications: Extrude Hone researchers disseminated their findings and received significant public attention through the following publications:

- Williams, R. E. "Monitoring Strategy for Flow Control in Abrasive Flow Machining," *in Advanced Materials: Development, Characterization, Processing, and Mechanical Behavior*. Published by American Society of Mechanical Engineers Materials Division and International Mechanical Engineering Congress and Exposition, Vol. 74, pp. 135-136, 1996.
- Rhoades, L. J., R. L. Resnick, T. O'Bradovich, and S. C. Stegman. "Abrasive Flow Machining of Cylinder Heads and Its Positive Effects on Performance and Cost Characteristics." *Proceedings of the Motorsports Engineering Conference*, Vol. 2, pp. 49-53, December 1996.
- Bartlett, J. "98 Ford Contour SVT." *Motor Trend*, March 1997.
- Smith, S. C. "Four-Door Party Animals." *Car and Driver*, March 1997.
- Olson, T. "Global Warming Policy Won't Hurt U.S. Jobs, Clinton Official Says." *Tribune-Review*, September 1997.
- "AFM Delivers Punch to Automotive Engines." *Tooling and Production*, December 1997.

PROJECT HIGHLIGHTS
Extrude Hone Corporation

- "The 10 Best Engines of 1998." *WARD's Auto World*, January 1998.
- Brooke, L. "More Airflow for Ford's SVT V-6." *Automotive Industries*, February 1998.
- Murphy, T. "The Little Shop that Could." *WARD's Auto World*, February 1998.
- Williams, R. E., and V. L. Melton. "Abrasive Flow Finishing of Stereolithography Prototypes." *Rapid Prototyping Journal*, Vol. 4, No. 2, 1998.
- Williams, R. E. "Acoustic Emission Characteristics of Abrasive Flow Machining." *ASME's Journal of Manufacturing Science and Engineering*, Vol. 120, No. 2, pp. 264-271, May 1998.
- "Ten Best Engines." *WARD's Auto World*, January 1999.
- "Contour Becomes a Cult Car." *Autoweek*, February 22, 1999.
- Williams, R. E., E. L. Clark, O. Kinyungu, S. Sarikonda, and K. P. Rajurkar. "Application of a New Acoustic Emission Monitoring Technique to Nontraditional Machining." *Transactions of NAMRI/SME*, Vol. 28, pp. 263-268, 2000.
- Williams, R. E., H. L. Dunegan, E. L. Clark, and O. Kinyungu, "A New Acoustic Emission Monitoring Technique for Abrasive Flow Machining." *Proceedings of the 2000 Japan-USA Flexible Automation Conference*, July 2000.

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